

## Potential impact of climate change on porous asphalt with a focus on winter damage

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### Abstract

This paper investigates the impact and adaptation options of climate change on porous asphalt roads, specifically for the case of winter weather (freeze-thaw cycles) and road damage in the Netherlands. Changes in weather patterns pose a threat to the serviceability and long-term performance of roads, as up to half of road maintenance costs are attributable to weather stresses. Porous asphalt (PA) is of particular concern in the Netherlands, where its use has become mandatory, primarily for environmental (noise-reduction) concerns. In recent winters, ravelling and pothole damage have increased the discussion about cold weather performance of porous asphalt and the potential challenges of changing winter weather patterns. Current climate change impact research often produces results on a systemic, macro scale, and less is known about the regional impact to specific road types. To address this, we examine the correlation between historic winter weather and PA pavement performance, which is particularly sensitive to the freezing / thawing phenomena. That relationship is combined with Dutch regional climate models and used to analyse the potential physical and economic impacts of adapting to future climate change. This has implications on maintenance, design, and long-term planning of the road network in the Netherlands.

*Keywords:* climate change adaptation; porous asphalt; freeze-thaw; roads; long-term planning

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## 1. Introduction

This paper investigates the impact and adaptation options of climate change on porous asphalt roads, specifically for the case of winter weather (freeze-thaw cycles) and road damage in the Netherlands. Changes in weather patterns pose a threat to the serviceability and long-term performance of roads, as up to half of road maintenance costs are attributable to weather stresses (Nemry et al. 2012). Porous asphalt (PA) is of particular concern in the Netherlands, where its use has become mandatory, primarily for environmental (noise-reduction) concerns. In recent winters, ravelling and pothole damage have increased the discussion about cold weather performance of porous asphalt. Current climate change impact research often produces results on a systemic, macro scale, and less is known about the regional impact to specific road types. To address this, we examine the correlation between historic winter weather and PA pavement performance, which is particularly sensitive to the freezing / thawing phenomena. That relationship is combined with Dutch regional climate models and used to analyse the potential physical and economic impacts of adapting to future climate change, which has implications on maintenance, design, and long-term planning of the road network in the Netherlands.

The research is conducted using a combination of empirical data analysis, climate and cost modelling. Historic winter maintenance data is recorded by Rijkswaterstaat, the ministerial road authority of the Netherlands, and winter weather data is provided by KNMI, the Dutch meteorological institute. By analysing these databases for correlations between weather and damage, a stressor-response function is developed that relates the frequency of freeze-thaw cycles to the frequency of pavement damage. The stressor-response function is incorporated into the previously developed Infrastructure Planning Support System (IPSS), which analyses the impacts and costs of different adaptation options for climate change and infrastructure (Chinowsky et al. 2011). To increase the granularity of analysis and produce regional (provincial) level results, down-scaled Dutch regional climate models (RCMs) are used. The results of IPSS are presented as an annual economic impact (costs) of each adaptation strategy from the current year until 2100.

The research is currently in progress. The changes in winter climate and impact on road damage are expected to vary regionally within the Netherlands. The IPSS results will highlight regions where proactive adaptation may create costs savings, as well as regions where adaptation is not financially advantageous. Discussion will contain practical implications for Rijkswaterstaat, both for short and long-term planning and policy decision-making. Of particular interest are the long-term viability and maintenance considerations of PA pavement in the future climate conditions. Adaptation strategies, pavement characteristics, and cost data are based on actual maintenance and design practices of the organization, which will result in output and recommendations that are both relevant and actionable for the Netherlands Ministry of Transportation.

### *1.1. Climate change and road national authorities*

Climate change adaptation research has been a quickly growing field as scientists and practitioners now acknowledge that even with mitigation the planet will experience certain unavoidable levels of climate change (IPCC 2007). While the questions of how much and when the changes will occur are still debated, there is a search for improved understanding of the potential impacts on transport infrastructure from future climate change. There are also several detailed research works that have analysed specific material responses to climate change, such as pavement implications (Mills et al 2009). As a larger quantity of data is produced, it is important to examine the scientific robustness, but also the relevance and usability of that information for the infrastructure designers and operators.

Organizations, often public organizations, are now and will continue to be responsible for planning and implementing climate change adaptation measures in the future. This is especially true for the transportation infrastructure sector, which is primarily managed by public agencies and requires long-term planning for both design and maintenance. In order to anticipate and plan for changes that may be required in the uncertain future, these agencies require information that is more detailed than sector-wide analysis but less in-depth than material property studies. The research project described in this paper builds on those efforts by combining economic modelling and material science while also maintaining an organizational perspective. The work intends to advance the science of climate change adaptation research through improvements to the cost modelling methodology, while also producing results that are more relevant and implementable at the organizational level.



Within the transportation sector highway organizations face a difficult challenge, as roads are a particularly vulnerable part of infrastructure. For example, as much as half of road maintenance costs are attributable to weather stresses (Nemry and Demirel 2012). Roads are designed to operate with minor variability in weather but long-term changes in climate are not accounted for in current planning and design standards. Changes in temperature and precipitation may result in positive outcomes, in the form of warmer winters for example, but also potentially severe negative outcomes from increased rainfall and higher temperatures (Peterson et al. 2008). It is important for transportation (highway) agencies to understand and adapt to these impacts for the end-users safety, for their own organizational benefit (e.g. cost and resource efficiency) and also because of the role that roads play in national commerce and international trade. Consequently, as the need for evaluation of adaptation options and costs has been established, research on climate change and roads has become increasingly quantitative, highlighted in the U.S. by Chinowsky et al (n.d.). However, these economic modelling results are not intended to be organization-specific but rather to inform at the national policy level (Jotzo 2010).

### *1.2. Climate change adaptation and road infrastructure*

Climate change research has evolved from focusing primarily on mitigation to include the exploration and evaluation of adaptation options. While there continues to be debate over the merits and means of mitigation, there is general consensus that some form of adaptation will be required to address the amount of climate change that is now unavoidable (IPCC 2007). Economic modelling of the impact and adaptation costs has been completed in many industry sectors, especially in agriculture and water resources (Tol 2002). This broad quantification of the potential impacts is an important tool for economists and policy-makers. But as Jotzo states in his report on the limitations of economic modelling for climate change adaptation, more detailed sector-specific modelling is required to enable local adaptation action (Jotzo 2010).

This is true within the transportation sector and there are an increasing number of studies, (Jaroszweski et al. 2010, Peterson et al. 2008, TRB 2008) that examine the risks of climate change to transportation infrastructure. Specifically, higher temperatures and increased precipitation will result in the acceleration of road degradation, primarily through rutting and ravelling. The quantification and modelling of cost impacts is being researched (Chinowsky et al. n.d., Nemry and Demirel 2012), however there are still few detailed studies, such as Mote et al. (2012) in the United States, which analyse climate and road characteristics that are unique to a specific organization. As stated in a report on climate change impact to European Union rails and roads, “Both vulnerability and adaptation costs would need to be assessed under a much higher spatial resolution” (Nemry and Demirel 2012).

Sector-specific modelling has been completed for road transportation using the Infrastructure Planning Support System (IPSS). This support system was developed by the Institute for Climate and Civil Systems at the University of Colorado Boulder to model the cost impact of adaptation options for climate change and road infrastructure. In addition to the social benefits of roads in developing countries, this work also detailed the importance of roads to the overall economic success of a country (P. Chinowsky et al. 2011). This is especially true for the highway system of the Netherlands.

## **2. Porous asphalt**

### *2.1. PA Background*

Porous asphalt (PA) pavement is characterized by a high percentage of interconnected voids in the top friction layer of the pavement. This creates high permeability and is also capable of reducing tire noise. The maximum aggregate size used in single layer porous pavements is 16 mm with a layer thickness of 50 mm and a built-in air void of 20%. Standard bitumen without modification is used for single layer porous pavements. In 2007, the bitumen percentage was increased from 4.2 to 5.2% and this is considered to increase the lifetime of the pavements by around 20%. For two-layer porous asphalt the maximum aggregate size in the top layer is normally 8 mm (Vejdirektoratet, 2012).

A major motivation for its use in the Netherlands is the cost and space efficiency is higher than sound barriers (Alvarez et al. 2006). PA pavements also have high resistance to rutting (Miradi 2009). Despite these benefits of porous asphalt, there are drawbacks that are important to consider in the context of climate change. Porous asphalt has a limited lifespan that is shorter than most alternative pavement types (Miradi 2009), it is susceptible



to increased ravelling and accelerated aging from rainwater and de-icing salt (Su 2013), and it has been shown that noise reduction effectiveness can be significantly reduced with age and clogging of pores (Bendsten et al. 2005). These will be important for RWS to consider when evaluating the long-term effectiveness of PA pavement in a changing future climate.

As described previously, the Dutch include environmental concerns in their road network planning. This includes the impact of road construction to the surrounding environment, as well as quality of life for nearby citizens. With a small land area and dense road network, residents in the Netherlands often live near highways and noise reduction is therefore an environmental consideration for road and land use planning. As the population grows and the use of automobiles increases, RWS has made noise reduction a priority (Van der Valk 2002, Huurman et al. 2010). As a result, as well as for additional reasons such as drainage, the Dutch road network is now constructed with approximately 90% porous asphalt pavement. This reliance on PA pavement increases the importance of climate change considerations in long-term planning of the Netherlands road network.

## 2.2. Historical behaviour of porous asphalt in winter

The expected lifetime of single layer porous asphalt is one to two years less than for dense asphalt concrete. In the Netherlands experience has shown that the approximate service life for porous asphalt wearing courses is 10 years versus 12 years for dense asphalt concrete (Van der Zwan, et al., 1990). The most often cited mode of deterioration for porous asphalt is ravelling, which primarily occurs during the winter season. PIARC (1993) states that rutting or cracking rarely appears in porous asphalts, except for reflection cracks, and that loss of material is one of the major reasons for road maintenance.

The 2009/10 and 2010/11 winters were severe, characterized by heavy snowfall and frost as well as many freeze-thaw cycles. This resulted in damage to Dutch roads, which was observed on all types of pavements. But as 90% of the high-way network has porous asphalt, the damage was mainly experienced by these pavement types. The damage observed consisted mostly of ravelling, potholes and material loss at longitudinal joints between porous asphalt (see Figure 1).

Additionally, damage was mainly on pavements at the end of their expected lifetime. Old porous asphalt is more sensitive to frost damage in hard winters because the bitumen hardens as the pavements gets older. As noted previously, older pavement is also shown to be less effective at noise reduction. Small cracks develop on pavements with aged and hardened bitumen. Water penetrates into these cracks and in periods of frost the water freezes and aggregate loosens from the pavement surface



Figure 1: Frost damage on porous pavement (RWS, 2012)

Potholes also contributing to accelerated road degradation in porous asphalt. For instance, emergency lanes become clogged and when they are not cleaned, water collects in the pores of the pavement in the summer period. This can result in the mortar/bitumen stripping from the aggregate and the damage can be accelerated by freeze-thaw cycles in the winter. Most of the frost damage has occurred on old pavement sections, which according to the Dutch pavement management system are already schedule for replacement. A delay in planned maintenance work, especially on porous asphalt, can cause additional frost problems (Vejdirektoratet, 2012).



A severe winter is statistically seen only once in every ten years in the Netherlands. Therefore, frost damage is considered by the national road administration as a calculated risk that happens, on average, once in ten years. As seasonal climate patterns change, this risk will also change. Rijkswaterstaat recognizes the need for more fundamental research into the causes of frost damage and the results may make it possible to develop better frost resistant mixtures of porous asphalt. In 2010, Rijkswaterstaat published guidelines for handling asphalt pavements including porous pavements (RWS, 2010). One method for improving frost resistance is through the use of more bitumen in pavement mixes. This will increase the cost of porous asphalt, however, and may not be effective under different climate conditions in the future.

### 2.3. Temperature monitoring

The Road Weather Information System (RWIS) is a continuous monitoring system for early warning of slipperiness on highway pavement surfaces. The RWIS system consists of 285 Road Weather Stations (RWS) combined with small local meteorological measuring stations. These stations are used to produce warnings of potentially upcoming slippery situations based on road surface temperature, resistance (dry, wet, or salt), dew point, and precipitation.

For this project we have analysed road surface temperatures at two locations on highway A10, with embedded temperature sensors, as shown in Figure 2. Road temperatures are measured in the surface layer and air temperature is measured beside the road in the small weather station. In order to establish correlations between official meteorological stations, road temperatures were initially correlated to the air temperature immediately adjacent to the road. This was then correlated to temperatures measured at the nearest meteorological weather station, in this case KNMI Schiphol weather station. Temperature measurements were correlated for the period of 3 years. Results are presented in the Figure 3 a) to d).



Figure 2: Location of road sensors on highway A10 and KNMI weather station

The goal of this part of the research was to establish numerical correlations that can be used for translating air temperatures into pavement temperatures, where no direct measurement of the road surface temperatures exist. The established correlations will be then used in predicting frost damage that is dependent on road temperature. As seen in Figure 3 below, the temperature conversion equations have very high correlation factors and are appropriate for the modelling purposes.

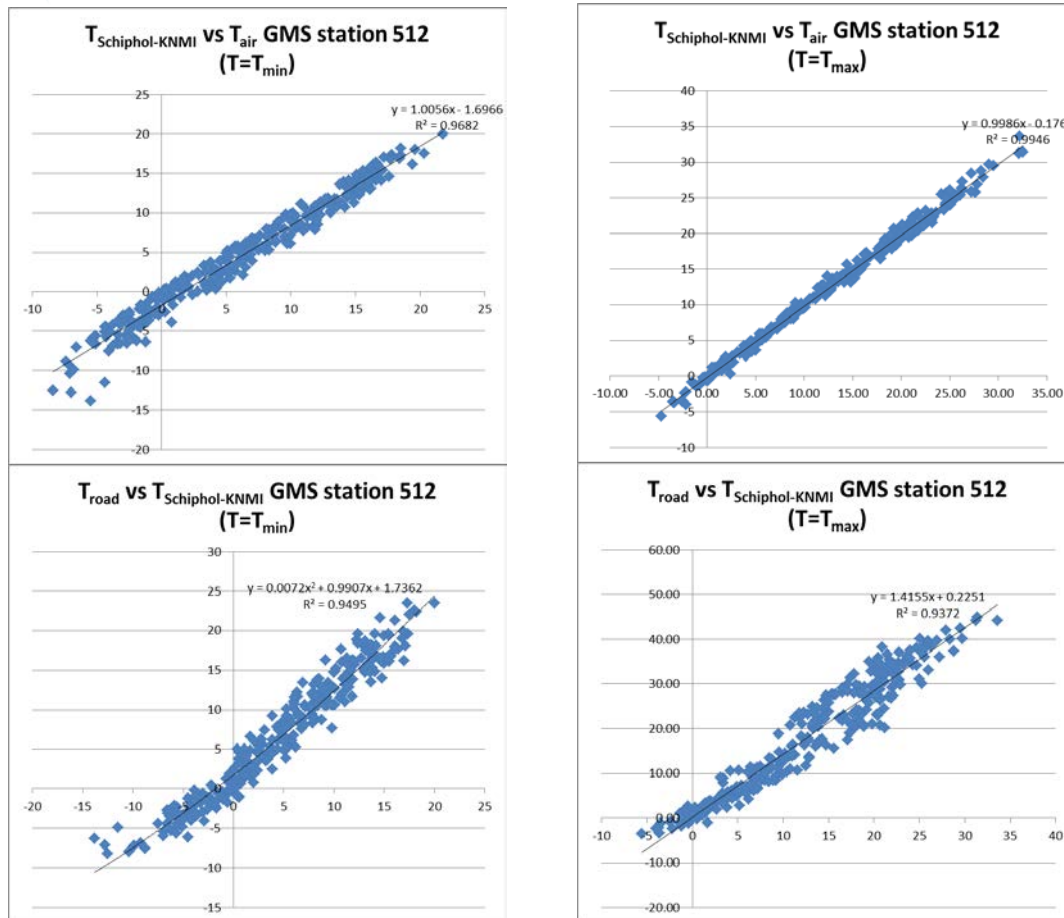


Figure 3: Results of temperature analysis: a) correlation between minimum air temperature measured beside the road and with official KNMI station; b) correlation between maximum air temperature measured beside the road and with official KNMI station; c) correlation between minimum road temperature and air temperature measured at the KNMI station; d) correlation between maximum road temperature and air temperature measured at the KNMI station.

### 3. Modelling of climate change impact

The research is conducted through a combination of climate modelling, empirical data analysis, and modification of the existing climate change adaptation modelling system, IPSS. The model has been used for several case studies, including countries in Europe (P. Chinowsky et al. 2011). Until now the model has been used primarily for developing countries and focused on temperature and precipitation stressors. Using the Netherlands as a case study, the IPSS model is expanded to include country-specific road characteristics (see Table 2 below), freeze-thaw impacts, and increased granularity of analysis. Incorporating country-specific road design and maintenance data strengthens the relationships between climate stressors (freeze-thaw cycles) and physical road response (damage).

Table 2: Porous Asphalt Road Characteristics, By Type (Van der Wal 2005)

Road Type		RL	LL
DAB	Service life	12 years	18 years
	Construction costs (compared to DAB)	1	
	Maintenance costs (compared to DAB)	1	
ZOAB	Service life	11 years	9 years
	Construction costs (compared to DAB)	1,02	
	Maintenance costs (compared to DAB)	1,05	
ZOAB TW	Service life	9 years	13 years
	Construction costs (compared to DAB)	1,12	
	Maintenance costs (compared to DAB)	1,80	



### 3.1. Infrastructure Planning Support System (IPSS)

Cost modelling is completed using IPSS, the climate adaptation modelling system designed by the Institute for Climate and Civil Systems (iCiCS) at the University of Colorado Boulder. Previous versions of the IPSS model analysed paved, gravel, and dirt roads primarily for developing countries. This research expands on the paved road portion of the model by including freeze-thaw analysis and focusing on porous asphalt road type.

Climate data is incorporated into the analysis on a 0.5° by 0.5° (longitude/latitude) grid for temperature and precipitation changes through 2100. Using higher resolution regional climate models, additional analysis is performed at the 0.25° by 0.25° scale. The forecasted climate change within each grid cell is applied to the total length of roads located in that same grid. This process quantifies the physical impact on road performance and design life into costs of adaptation, as outlined below.

The model uses thresholds and stressor-response functions to predict the impact that changes in climate stressors, in this case the total number and frequency of freeze-thaw cycles, will have on a road. The functions compare changes in quantities of freeze-thaw cycles to historic road and weather data, which are used to set thresholds at which freeze-thaw is shown to begin negatively affecting road performance. If the future freeze-thaw patterns exceed these thresholds, changes in design or maintenance will be required to “climate-proof” the road against the change in climate. In Chinowsky and Arndt (2012), more detailed explanation of the functions, stressor-response methodology, and thresholds can be found. Chinowsky et al (2013) also provides background on the impact functions and underlying assumptions of the model. For this case study, the basic assumptions and process of the model remain the same. However, Dutch road design parameters – including cost, lifespan, and pavement type – replace the original IPSS road inputs. Combined with the downscaled climate modelling, this modifies the system to produce results that are organization-specific and on a finer spatial scale than previously attained.

The IPSS results are calculated based on two alternate adaptation strategies. A “no adapt” strategy calculates costs based on increased maintenance that is required to preserve the intended design life of the road, without altering the initial design of that road. The “adapt” strategy calculates costs for altering the initial design of a road with increased climate resiliency during its lifespan, rather than preserving the initial design life exclusively through maintenance. The adaptation evaluation is performed at the beginning of each road’s design life. If the climate model forecasts that a threshold will be crossed (i.e. the number of freeze-thaw cycles has increased) during a road’s design life, the cost for adapting and not adapting are then calculated. For this project it was crucial to use data from RWS in the Netherlands in order to produce quantitative results that are based on actual costs, policy, and procedure, making them more actionable for the infrastructure planners.

### 3.2. Climate

*modelling*

In addition to the global climate models that IPSS typically utilizes, this case study includes downscaled climate data that is specific for the Netherlands’ region of Europe.

#### *Climate description of the Netherlands*

The Netherlands has a temperate maritime climate, with cool summers and moderate winters. The country is small and, as a result, there is little variation inland; although the influence of the sea is noticeable in the western part of the country. Daytime temperatures vary from 2-6 °C in wintertime and 17-20 °C in summertime. Precipitation is distributed equally throughout the year.

#### *Regional Climate Model Simulations*

Regional Climate Models (RCMs) are a complementary research method to the coarser resolution Global Climate Models (GCMs). High resolution is one key advantage of RCMs (spatial resolution of 25-50 km) compared with GCMs (spatial resolution at best around 100-200 km), especially in regions with variable land forms or characteristics. The quality of a RCM simulation, with a spatial resolution of 25-50 km, is dependent by the RCM itself and by the driving GCM.

The ENSEMBLES project was a large research program founded by the European Commission in 2004. The main aim, and core, of the ENSEMBLES project was running multiple climate models (‘ensembles’) with the



aim to produce a range of future predictions assessed to decide which of the outcomes are more likely (probable) than the others.

In the ENSEMBLES project, fifteen institutes ran their RCMs at 25 km spatial resolution, with boundary conditions from five different GCMs, all using the same SRES emission scenario. In this study it was decided to use one model per institute and only those models that extended their simulation until 2100. This leads to Table 1 that lists the eight models that are used in this study (ENSEMBLES 2009).

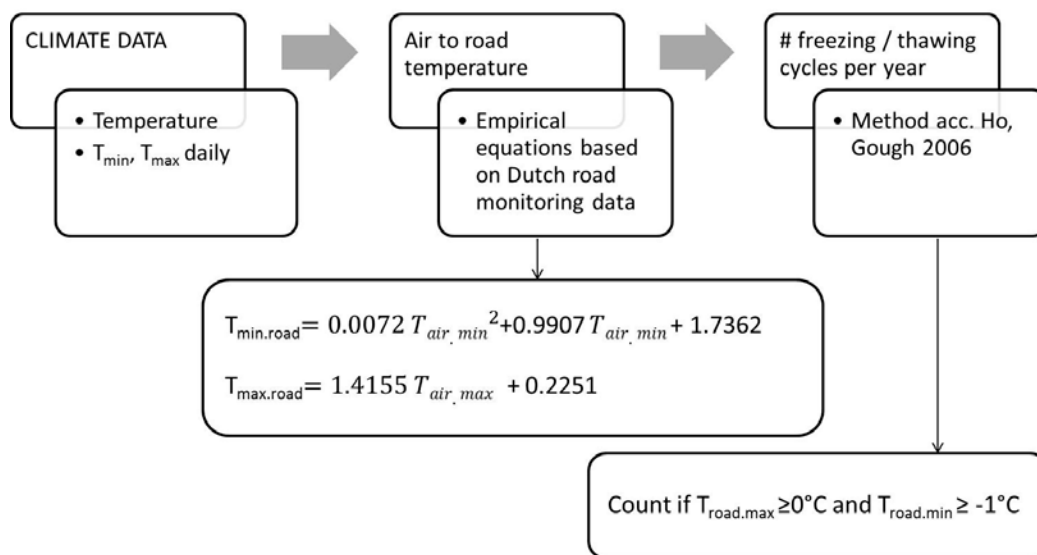
Table 1: List of RCMs used in this study with their driving GCMs

RCM	Driving GCM	Reference
CNRM ALADIN	ARPEGE	(Radu, et al. 2008)
DMI HIRHAM	ECHAM5	(Christensen, et al. 2006)
ICTP REGCM	ECHAM5	(Pal, et al. 2007)
KNMI RACMO	ECHAM5	(Van Meijgaard, et al. 2008)
MPI REMO	ECHAM5	(Jacob 2001)
SMHI RCA	BCM	(Kjellström, et al. 2005)
METOFFICE HadRM	HadCM3	(Pope et al. 2007)
ETH CLM	HadCM3	(Böhm et al. 2006)

### 3.3. Modelling frost damage

The number of freeze-thaw cycles is calculated using the method according Ho & Gough (2006), which counts if maximum temperature  $\geq 0^{\circ}\text{C}$  and minimum temperature  $\leq -1^{\circ}\text{C}$ . Pavement temperature is needed to calculate the number of freeze-thaw cycles. To calculate pavement temperature, the forecasted air temperature from climate models (daily minimum and maximum) is converted using the correlation equations derived from Dutch weather station and pavement sensor data. These equations are presented in Figure 4 below.

Figure 4: Flow chart of the input climate related input parameters for predicting frost damage







Based on analysis of the correlation between historic winter weather data and road damage, the threshold at which damage is expected to increase due to freeze-thaw cycles is 20 cycles per month. Each additional increase in 5 cycles will create further damage, thus thresholds are set at 20, 25, 30, and 35. If the number of freeze-thaw cycles increases beyond one of these thresholds during the lifespan of a road, the costs for both “adapt” and “no adapt” strategies are then calculated.

Adaptation requires that the road design is altered before being repaved. To redesign the road for increased levels of freeze-thaw, costs will be incurred. This is captured in the SCI (stressor cost increase) variable, which is either calculated as the costs associated to modify pavement design (e.g. increase bitumen content, decrease aggregate size) or the costs of constructing a different pavement type, whichever is more appropriate given the anticipated threshold. General equations used for this calculation are presented below:

$$\text{Equation 1) } C_{\text{adapt}} = (N_{\text{thresh}} * \text{SCI}) * B_{\text{PG}}$$

Where

- $C_{\text{adapt}}$  = increased cost due to climate change adaptation
- $N_{\text{thresh}}$  = number of thresholds crossed during road lifespan
- SCI = Stressor cost increase
- $B_{\text{PG}}$  = base construction cost = resurfacing costs

Following the no adaptation strategy, the road design is not modified and damage will increase if thresholds are crossed. In this case, additional maintenance to repair the damage is required in order to preserve the original road design life. The increased costs are calculated by multiplying original winter maintenance costs by the expected percentage increase in damage, as calculated above during the threshold analysis. The advantage of this strategy is that the cost of additional maintenance may be less than the cost to modify the pavement design and construction. General methodology for calculating “no adapt” costs are presented below.

$$\text{Equation 2) } \text{MT} = L_{\text{ERB}} * C_{\text{ERB}} * L_{\text{road}}$$

Where

- MT = increased maintenance costs due to climate change
- $L_{\text{ERB}}$  = % change (decrease) in lifespan associated with a unit change in climate stress
- $C_{\text{ERB}}$  = current/base frost-related maintenance costs per km per year
- $L_{\text{road}}$  = length of roads affected by frost damage

#### 4. Conclusion

The combination of Rijkswaterstaat’s reputation for long-term planning, strict maintenance procedures, and recent budget constraints (RWS 2012) further highlights the need for adaptation analysis that addresses their organization and regional priorities, not only sector-wide concerns. To obtain this, the research incorporates local empirical information, such as weather station and pavement sensor data. Combined with detailed climate models, pavement material properties, and organizational cost data, the IPSS freeze-thaw modelling produces more accurate and actionable results than what is currently incorporated into existing decision-making. This improves support for design, maintenance, and long-term planning within the organization.

It is particularly useful for the Netherlands to review the impacts of climate change in respect to analogous climate. The changing winter conditions and freeze-thaw patterns may be similar to environments regularly experienced by other countries, or by certain regions within the Netherlands. Taking this into consideration, the new design and maintenance strategies can be adjusted in advance to maximize the opportunity or minimize the impact. Unique to The Netherlands, however, is their reliance on porous asphalt. It is imperative for the long-term sustainability of their road infrastructure that PA roads will still be resilient and effective under future climate conditions.

As initial results from the freeze-thaw analysis in IPSS are being finalized, they support the thesis that in most regions it is not a question of if, but when adaptation will be required. The challenge that climate change presents for Dutch road infrastructure is both a short and long-term concern. The cost from precipitation and temperature impacts alone through 2100 in the Netherlands is as high as €21 billion (Kwiatkowski et al 2013). This cost will



increase as the freeze-thaw impacts are incorporated. If a proactive adaptation approach is properly managed, however, the Netherlands could save as much as €10 billion during that time. There are also potential opportunities from a changing climate in the Netherlands. In some regions, drier climate will require less robust drainage design and warmer winters could reduce freeze-thaw damage and subsequent maintenance on highways. The detailed level of analysis described in this paper is meant to better inform the Dutch infrastructure operators about the regional variability, as well as long-term trends that threaten the performance and operating cost of the road network.

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